

# Cochlear Electrical Model for the Interpretation of Tinnitus

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**Abstract** - If the model for the auditory system from ear canal to the auditory cortex is established, it would be great contributions to the diagnosis and treatment of tinnitus patients. In this study, existing models for the auditory system were examined, and a model which can best explain tinnitus phenomena was established. In a new model, reticular lamina, thin fluid layer which transmits energy in a cochlear, was assumed as a mass and the components for the stiffness and control were added to the model. Mathematical interpretation was performed to compare the zeros and poles of the transfer function between existing models and newly designed model. The results showed that the values of zeros were lower than that of the poles which coincides with the results obtained from animal neural data.

**Keywords** - Auditory system, Cochlear electrical model, Tinnitus, Electrical stimulation, Reticular lamina

## I. INTRODUCTION

To understand the exact mechanisms of the processes about sound transmission in the auditory system, theoretical and quantitative characteristics of the system should be established. One of the ways to achieve such goal is through the electrical and/or mechanical modeling [1-3]. That is, if we could find the model for the auditory system, from auricles to the auditory cortex, it could be used as a useful tool for the understanding of pathological disorders. Also, it may be possible to establish the protocols for an appropriate diagnosis and treatment for the patients.

Tinnitus is the condition that one feels the sound without external sound sources even in the completely silent environment [4]. Approximately 95% of populations have experienced the tinnitus and almost 20% of populations have a severe attack of tinnitus which causes intense inconvenience in normal life. In an extreme case, tinnitus would be the cause of depression. Therefore, it calls for the development of quantitative methods for the diagnosis and treatment of tinnitus.

Objectives of this study were to establish a model, which could be used as a reference for the diagnosis and treatment of the tinnitus. Existing models for the auditory systems were examined, then a model that can best explain tinnitus phenomena was established. Mathematical interpretation was performed to compare the zeros and poles of the transfer function between existing model and newly designed model. This study will be extended to an animal experiment to verify the validity of the designed electrical model and to demonstrate the effect of electrical stimulation for the treatment of tinnitus.

## II. COCHLEAR ELECTRICAL MODEL

Applied acoustic pressure to the Reissner's membrane induces the vibration of basilar membrane, and causes the energy flow in the cochlea based on the forces, which act as sinewave function. To understand the precise function of the inner ear, followings should be understood first: the mechanisms of the basilar membrane and reticular lamina,

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an independent movement of the tectorial membrane, a force generation in the inner and outer hair cells, an influence of stereocillia's twist and bend, an effect of fluid flow from the vestibular to the scala tympani, and a nonlinear relationship with each organ.

A new cochlear model shown in Fig. 1 was established based on the Allen's two-dimensional inner ear model. Reticular lamina was regarded as a mass, which generates the shear force to the hair cells. It also amplifies the transmission of phase to the tectorial membrane [5]. It implies that the reticular lamina could form the shear force to the hair cells and amplify the phase of transmission to the tectorial membrane.

Movement of mass is expressed as  $X = a \sin(\omega t)$ , where  $a$  and  $\omega$  are an amplitude of oscillation and an angular velocity, respectively. Therefore, it could be expressed as below, where  $K$  is a spring constant.

$$\begin{aligned} v &= a\omega \cos(\omega t) = a\omega \sin(\omega t + \pi/2) \\ F &= -KX = aK \sin(\omega t) = aK \sin(\omega t + \pi) \end{aligned} \quad (1)$$

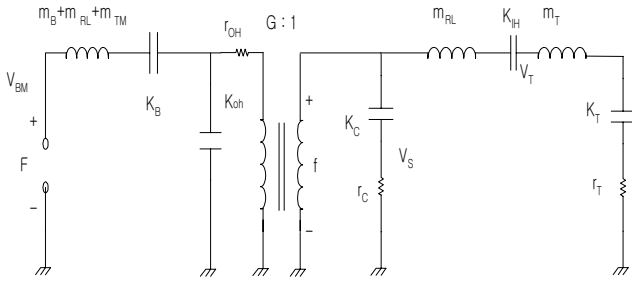


Fig. 1. Two-dimensional cochlear electrical model considering reticular lamina as a mass.

$V_{bm}$  : voltage of basilar membrane,  $m_B$  : mass of basilar membrane,  $m_{RL}$  : mass of reticular lamina,  $m_T$  : mass of tectorial membrane,  $K_B$  : stiffness of basilar membrane,  $K_{OH}$  : stiffness of outer hair cell,  $r_{OH}$  : damping of outer hair cell,  $G$  : gain which transforms vertical motion to radial shear motion,  $K_C$  : stiffness of cilia,  $r_C$  : damping of cilia,  $K_{IH}$  : stiffness of inner hair cell,  $K_T$  : elastic connection to the scala wall,  $r_T$  : damping loss across  $K_T$

Changes in velocity and force cause the displacement of the membrane by  $\pi/2$  and  $\pi$ , respectively. Since the displacement of above  $\pi/2$  is generated from the negative forces, vibration energy would be reduced. If the reticular lamina was assumed as a layer, amplification occurs when either bundle of hair cells moves in the opposite side or voltage responses of outer hair cells appear in reverse direction. If the contraction of outer hair cell provides the cochlear amplification, there must be the special processes, which change the phase relationship among basilar membrane, reticular lamina, and outer hair cells.

### III. MATHEMATICAL INTERPRETATION

Transfer function, which relates the voltage values measured at the stereo cillia to the basilar membrane was examined with existing animal neural tuning data. Also, basilar membrane impedances were measured to justify the numerical formula.

Characteristics of transfer function regarding poles and zeros were expressed as a second order equation, and mathematical interpretation was performed to compare the zeros and poles of a transfer function. As can be seen from Fig. 2, the spectral zeros are systemically located below the characteristic frequencies and the poles are located above the characteristic frequencies [6, 7].

#### Characteristics of the Transfer Function

Transfer function was calculated as follows to prove the properties of the established model.

$$H_T(x,s) \equiv G \frac{s(m_T + m_{RL}) + r_T + (k_T + k_{IH})/s}{s(m_T + m_{RL}) + (r_C + r_T) + (k_{IH} + k_C + k_T)/s} \quad (2)$$

$$\omega_Z^2(x) = (k_T + k_{IH}) / (m_T + m_{RL}) \quad (3)$$

$$\omega_P^2(x) = (k_C + k_T + k_{IH}) / (m_T + m_{RL}) \quad (4)$$

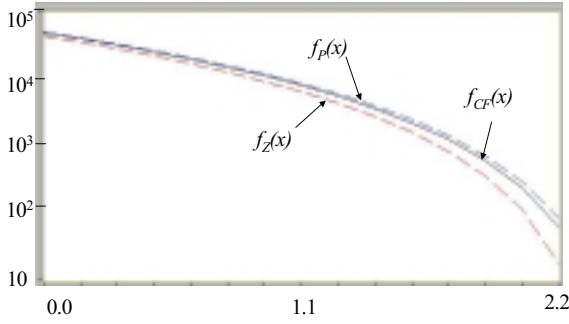


Fig. 2. Poles and zeros of the neural tuning curve calculated from the model at the characteristic frequency of 3.5kHz.

$$\zeta_z(x) = \frac{1}{2} r_T / \sqrt{[(k_T + k_{IH})(m_T + m_{RL})]} \quad (5)$$

$$\zeta_p(x) = \frac{1}{2} (r_C + r_T) / \sqrt{[(k_C + k_T + k_{IH})(m_T + m_{RL})]} \quad (6)$$

$$\gamma = \frac{\omega_p}{\omega_z} \quad (7)$$

Radian frequencies  $\omega_p$  and  $\omega_z$  are the pole and zero frequencies.

Including the damping ratio  $\zeta$ , normalizing variables  $\omega_z$ ,  $\omega_p$ ,  $\zeta_z$ , and  $\zeta_p$  are physically meaningful since they could be identified from the transfer function spectrum. The pole frequency appears to be above the characteristic frequency, which could not be observed in normal tuning data.

### Basilar Membrane Impedance

One of the critical points in macromechanics is the basilar membrane impedance, which is generally assumed to be the form of

$$Z_{BM} = K_B(x)/s + R(x) + sM_0 \quad (8)$$

which would be equivalent to the following equation derived from the model shown in Fig. 1.

$$Z_{bm} = K_B(x)/s + s(m_B + m_{RL} + m_T) + \frac{k_{OH} \cdot r_{OH}}{k_{OH} + r_{OH} \cdot s} + R(x) \quad (9)$$

Resistance to the shearing force  $R(x)$  could be calculated

with the use of the viscous fluid of viscosity, the width of upper plate, and the distance between upper and lower plate based on the viewpoint of fluid mechanics.

According to the definition of the transduction filter, basilar membrane could be rewritten as follow:

$$Z_{bm}(x, s) = s(m_T + m_B + m_{RL}) + K_B/s + \frac{k_{OH} \cdot r_{OH}}{k_{OH} + r_{OH} \cdot s} + \frac{k_C}{s} \left( 1 + \frac{s r_C}{k_C} \right) G(x) H_T(x, s) \quad (10)$$

where the cilia damping frequency is defined as  $\omega_C = k_C / r_C$ . Also,  $\omega_C \gg \omega_p$  given for  $\omega < \omega_p$

$\ll \omega_C$ . Since the constant  $|s r_C / k_C| = \omega / \omega_C$  is much lower than 1, it could be ignored in (10). From these processes, basilar membrane could be found as follows:

$$Z_{bm} = s(m_T + m_B + m_{RL}) + \frac{k_C G^2(x)}{(k_C + k_T + k_{IH})} \times \left[ s(m_T + m_{RL}) + r_T + \frac{(k_T + k_{IH})}{s} \right] \quad (11)$$

Basilar membrane could be expressed as a second order equation with the use of this impedance. Then, it might be possible to change each value, such as

$$k_C = (m_T + m_{RL}) \omega_p^2 (1 - 1/\gamma^2) \quad (12)$$

$$\omega_C / \omega_p = \varepsilon (m_T + m_{RL}) \omega_p (1 - 1/\gamma^2) / \eta l \quad (13)$$

By substituting each material frequency to (12) and (13), the range of  $\omega_C / \omega_p$  could be calculated. If the result and preceding assumption is compared, it could be possible to confirm the validity of the new model.

## IV. RESULTS AND DISCUSSION

New cochlear electrical model was proposed to interpret the tinnitus phenomena. Zero and pole frequencies, which

were calculated mathematically through the transfer function, justified the suggested assumption.

From the transfer function in equation (2),  $H_T$  could be expressed as

$$f_Z = (1/2\pi)\sqrt{(k_T + k_{IH})/(m_T + m_{RL})} \quad (14)$$

$$f_P = (1/2\pi)\sqrt{(k_C + k_{IH} + k_T)/(m_T + m_{RL})} \quad (15)$$

where  $f_Z > f_P$ , since  $(k_C + k_T + k_{IH}) > (k_T + k_{IH})$ .

The significance of this result is a spectral zero, which is required to account for the difference between the mechanical and neural response. A spectral zero was located below the characteristic frequency and a pole was located above the characteristic frequency [6]. From equation (15), approximations of  $\omega_C/\omega_P$  could be found with the value  $m_{RL}$  ignored since it's so small. According to the above equation, it could be found that  $\omega_C/\omega_P > 0.0124\omega_P$ . Hence for the approximation in the formula is justified.

From this study, complex and nonlinear characteristics of the inner ear for sound transmission could be accounted, and the new model, which could be applied to explain tinnitus was proposed.

## V. CONCLUSIONS

In a new model, reticular lamina, thin fluid layer which transmits energy in a cochlear, was assumed as a mass and the components for the stiffness and control were added to the model. The results showed that the zeros appeared to have lower values than that of the poles, which coincided with the results obtained from animal neural data. Also, commonly assumed model parameters showed consistencies with the model suggested from this study. Moreover, from the mathematical interpretation, which compares the zeroes and poles of the transfer function between existing model and a new model, similarities were found which demonstrate

the appropriateness of a new model.

This study will be extended to an animal experiment to verify the validity of a new model. It could possibly suggest a new viewpoint for the diagnosis and treatment of tinnitus.

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